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RESEARCH AND DEVELOPMENT

OF

AN OPTIMIZED LABORATORY SPEECH-COMPRESSION

SYSTEM FOR SPACECRAFT APPLICATIONS

TASK 6

SPACE MISSION APPLICATIONS STUDY

Contract No. NAS 9-4523 [redacted]

25 May 1966

Manned Spacecraft Center
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PHILCO CORPORATION
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SECTION 1

INTRODUCTION

The narrow-bandwidth speech-communication breadboard was built to demonstrate that speech information can be transmitted at relatively narrow bandwidths. This report is concerned with the application of the processing system with future lunar and interplanetary missions. It can be concluded that although narrow-band speech-communication equipment can benefit a lunar mission, it would be of most benefit to an interplanetary mission where large amounts of power would ordinarily be required.

However, for purposes of illustration, the lunar mission is considered in some detail to demonstrate the utility of the narrow-band processor. Among the more significant conclusions drawn from the study is the fact that the processing can benefit telemetry and other communication functions as well as the voice transmission. Comparisons of performance between processed and unprocessed speech are presented for both analog and digital systems. It was determined that as much as 12.7 db improvement can be gained by using a developed speech-processing equipment. A discussion of the sources and characteristics of noise in space as well as a discussion of modulation systems are also presented.

SECTION 2

SOURCES OF NOISE IN SPACE COMMUNICATIONS

The factor which ultimately limits the performance of any bandwidth-compression system is the presence of noise. The narrow-band speech processing system under study would be subjected to a number of different noise sources when actually placed in operation in a space vehicle. These sources of noise not only include amplifier noise, of which most designers are familiar, but they also include solar noise, Galactic Noise, Auroral Noise, discrete cosmic noise and others. This Section describes the characteristics and magnitude of some of these sources of interference.

2.1 SOLAR NOISE

The sun radiates high-intensity electromagnetic waves in excess of the equivalent blackbody intensity of 6000°K deduced from optical and thermal data. During sunspot activity, irregular increases of noise can last for periods of several days, and sudden bursts of a few seconds' duration may occur. Solar noise bursts appear most often at the high frequencies[1] and usually increase radio noise by approximately 20 db over the noise level of the quiet sun. The observed noise temperature at an antenna is dependent on the antenna beam size and frequency. Figure 2-1 shows experimental values of the apparent temperature of the quiet sun as a function of frequency[2] for a narrow beam pointing directly at the sun. For most applications, narrow antenna beams can be controlled to avoid pointing the main beam at the sun; however, there is no way to prevent noise from entering through the antenna sidelobes. Through careful antenna design, the sidelobe level can be kept isotropic for all angles more than six beamwidths away from the main beam.[3] The curve in Figure 2-1 represents

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1. R. Payne-Scott, D. E. Yaboly, and J. C. Bolton, "Relative Times of Arrival of Bursts of Solar Noise on Different Radio Frequencies," Nature, Vol. 160, 1947, p. 256.

2. J. L. Pawsey, and S. F. Smeral, The Sun, Chapter 7, University of Chicago Press, 1953.

3. C. T. McCoy, Space Communications, Philco Report 279, 2 June 1960.

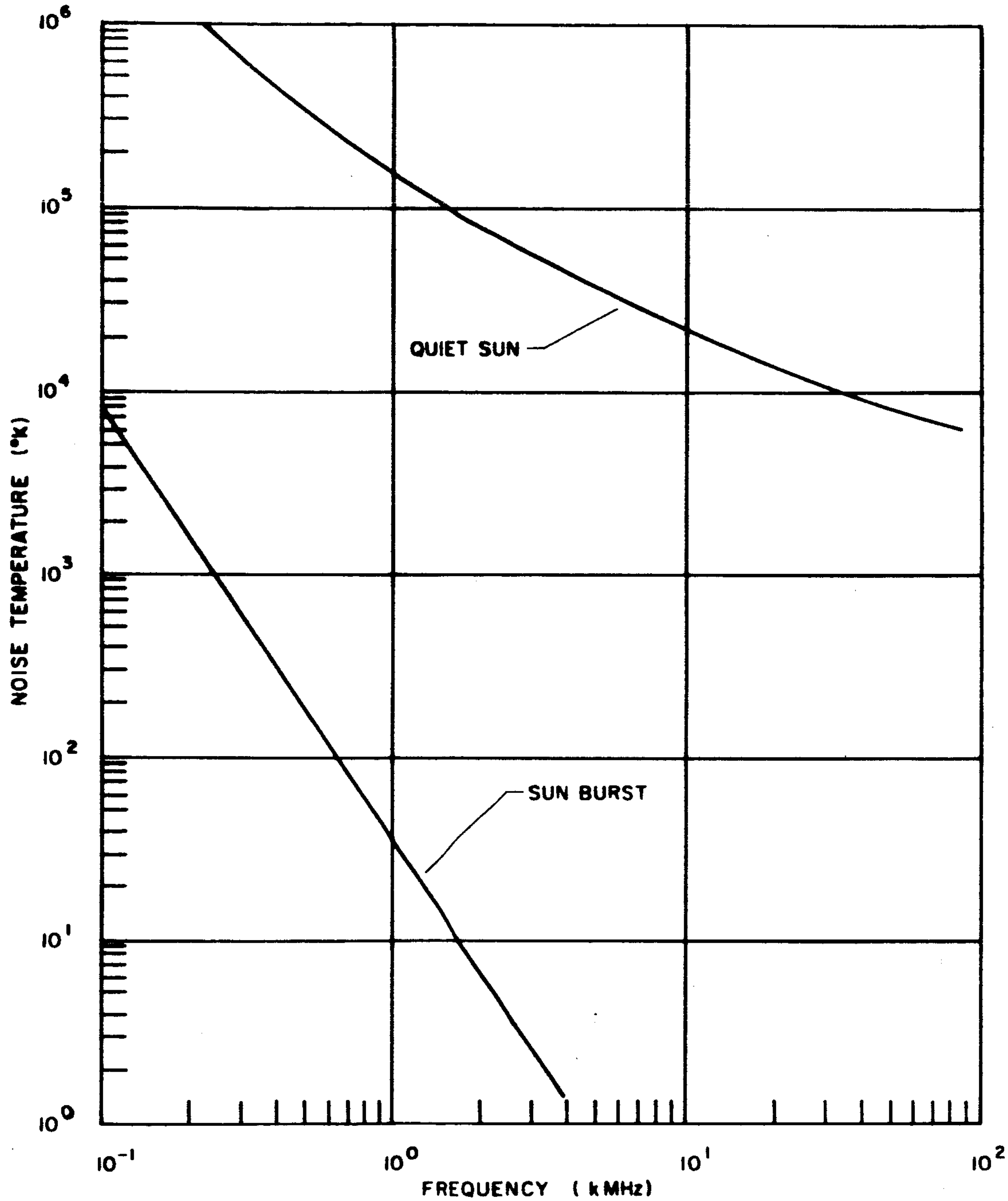

Figure 2-1. Solar Noise

the apparent noise temperature, assuming this isotropic sidelobe level and a burst condition of about 40 db above the quiet level. This solar burst noise can be expected no matter where the antenna is pointed during the burst duration.

2.2 GALACTIC NOISE

The main source of galactic noise is the center of the Milky Way, in the region of the constellation Sagittarius.[1] For convenience, the galactic noise sources can be put into three regions as shown in Table 2-1. The results of observations of the intensity and distribution of noise for these three regions are shown in Figure 2-2.[2]

Table 2-1. Galactic Noise Regions

Region	Galactic Coordinates		Equatorial Coordinates	
A	Latitude	-2°	Declination	-26°
	Longitude	330°	Right Ascension	17^h35^m
B	Latitude	0°	Declination	0°
	Longitude	180°	Right Ascension	6^h40^m
C	Latitude	-30°	Declination	-29°
	Longitude	200°	Right Ascension	5^h30^m

The maximum and minimum sky background temperatures due to galactic sources have been observed by others using very-high-resolution antennas.[3] The results of these observations agree very well with those

1. H. C. Ko, "The Distribution of Cosmic Radar Background Radiation," Proceedings of the IRE, January 1958.

2. J. H. Piddington, "The Origin of Galactic Radio Frequency Radiation," Monthly Notices of Royal Astronomical Society, Vol. 3, 1951.

3. J. D. Kraus, and H. C. Ko, Celestial Radio Radiation, RF Project 673, Scientific Report No. 1, Radio Observatory, Department of Electrical Engineering, Ohio State University, May 1957.

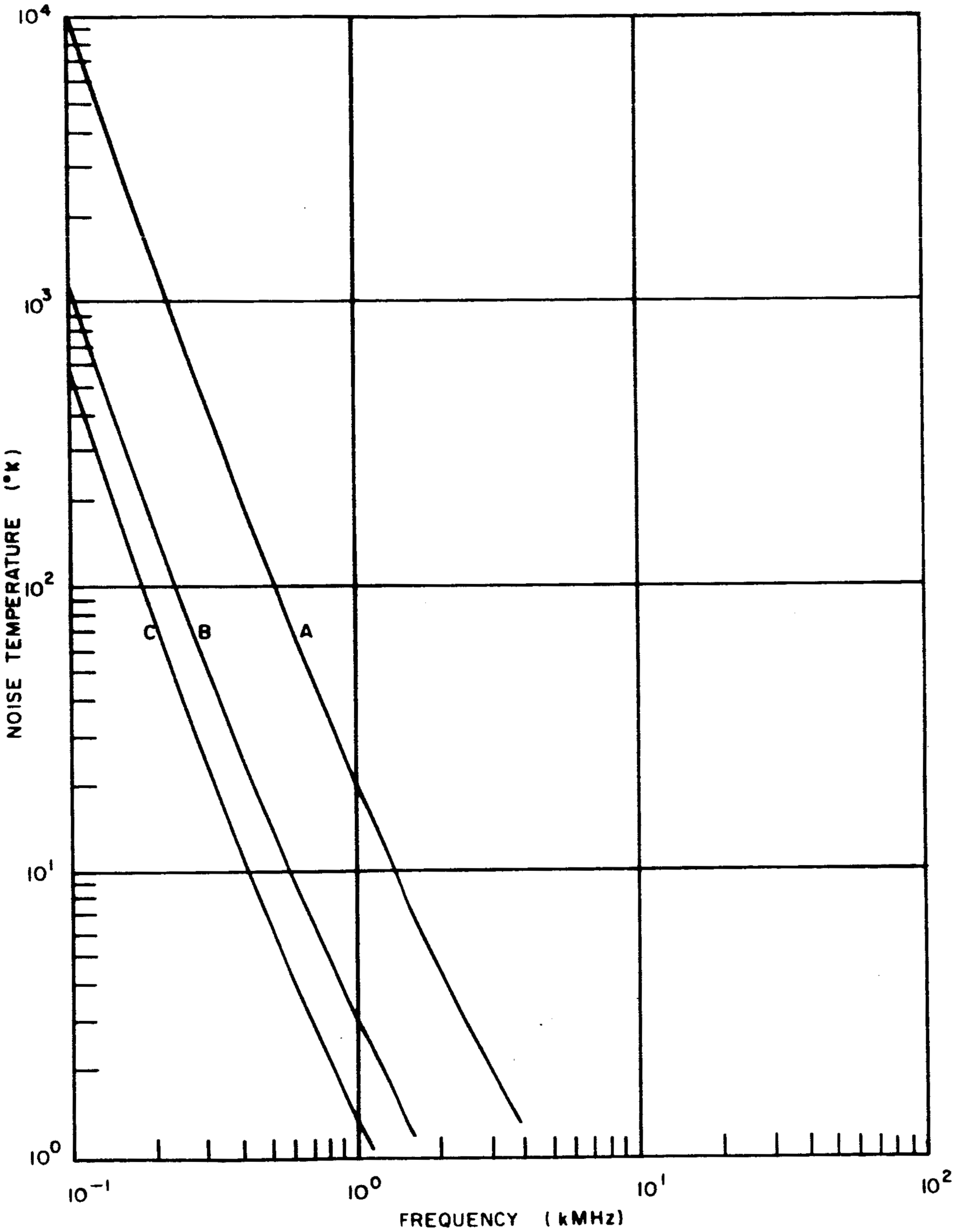

Figure 2-2. Galactic Noise (Galactic Regions A, B, and C)

of Figure 2-2. Since high-resolution antennas were used, the observations are a good approximation to the true sky temperatures.

2.3 RADIO STARS

Radio stars are called discrete sources because they are fairly well defined with regard to their intensities and positions in space.[1] The brightness temperatures of these sources as a function of frequency are shown in Figure 2-3. These would be the noise temperatures to be expected when an antenna is pointed directly at each source and the entire beamwidth filled with radiation from that source. Another so-called discrete source is the scattered atomic hydrogen radiation, whose frequency is approximately 1421 Mc. Radio astronomers have indicated that some of these sources have a noise intensity approximately equivalent to a 100°K blackbody radiator.

2.4 ATMOSPHERIC NOISE

Noise generated in the atmosphere is due to the moisture content of the atmosphere. This noise and the other earth-bound noise sources would affect the narrow-band speech-processing system if the receiver were located on the ground. The higher the moisture content, the greater the emissivity of the atmosphere. Emissivity of any blackbody for any frequency is identical with the absorptivity for that frequency or radiation. The apparent noise temperature can be expressed by the following relationship.

$$T_a = T\,(1 - G) + G\,T_b, \qquad (1)$$

where T_a is the apparent temperature, T is the thermal temperature of the absorbing medium, G is the power gain of the medium, and T_b is the noise temperature of the background source. G is less than unity because it corresponds to absorption. Equation (1) shows that, for high absorption ($G = 0$), T_a approaches the thermal temperature of the medium, T, and when absorption is negligible ($G \approx 1$), the antenna temperature approaches the background noise, T_b. The antenna temperature due to the atmosphere can be calculated only by noting the loss of the atmosphere as a function of frequency, assuming an atmospheric temperature of 300°K and employing the first half of Equation (1). The results of this calculation are shown in Figure 2-4.

1. H. I. Ewen, "A Thermodynamic Analysis of Maser Systems," Microwave Journal, Vol. 2, No. 3, March 1959.

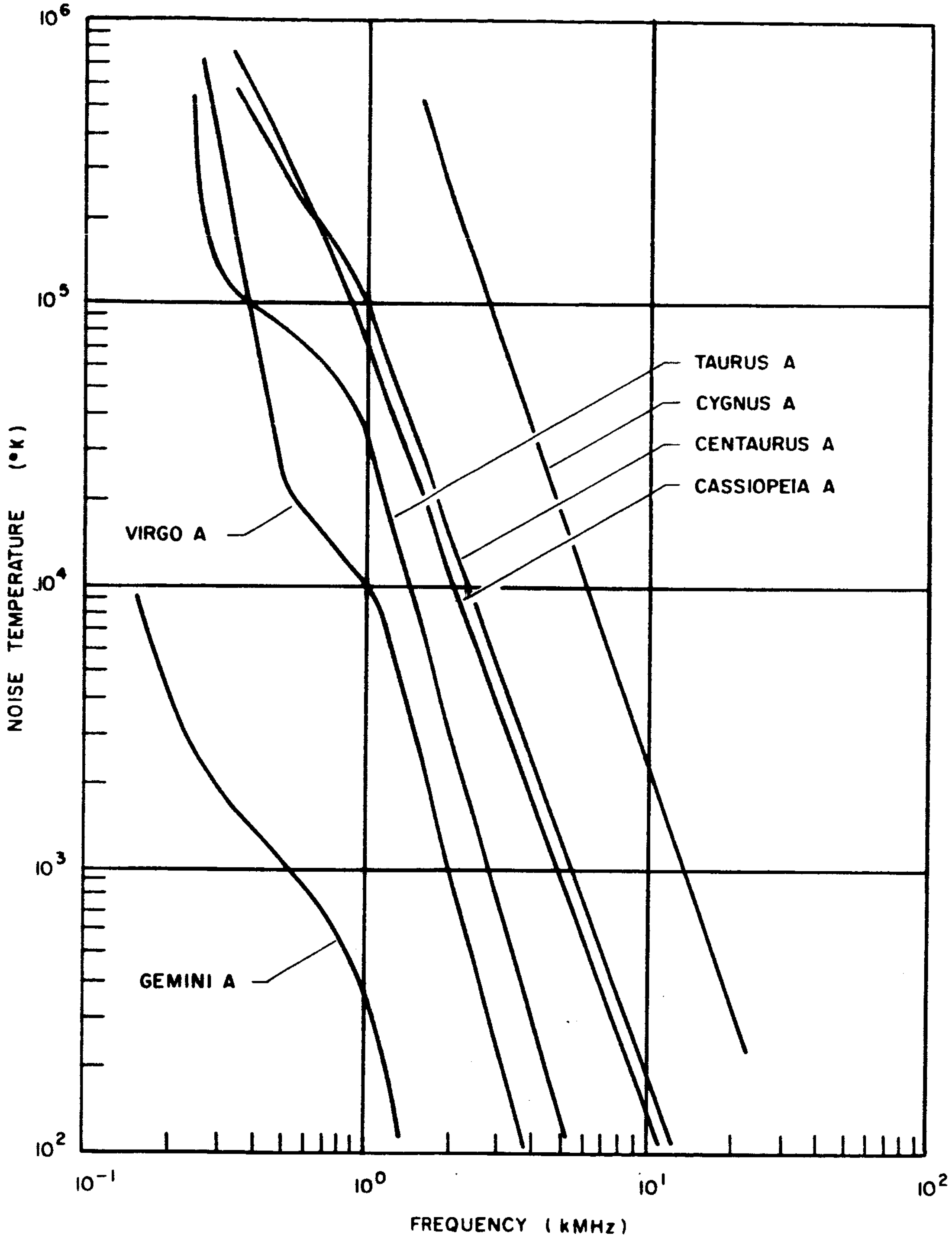

Figure 2-3. Noise From Discrete Cosmic Sources

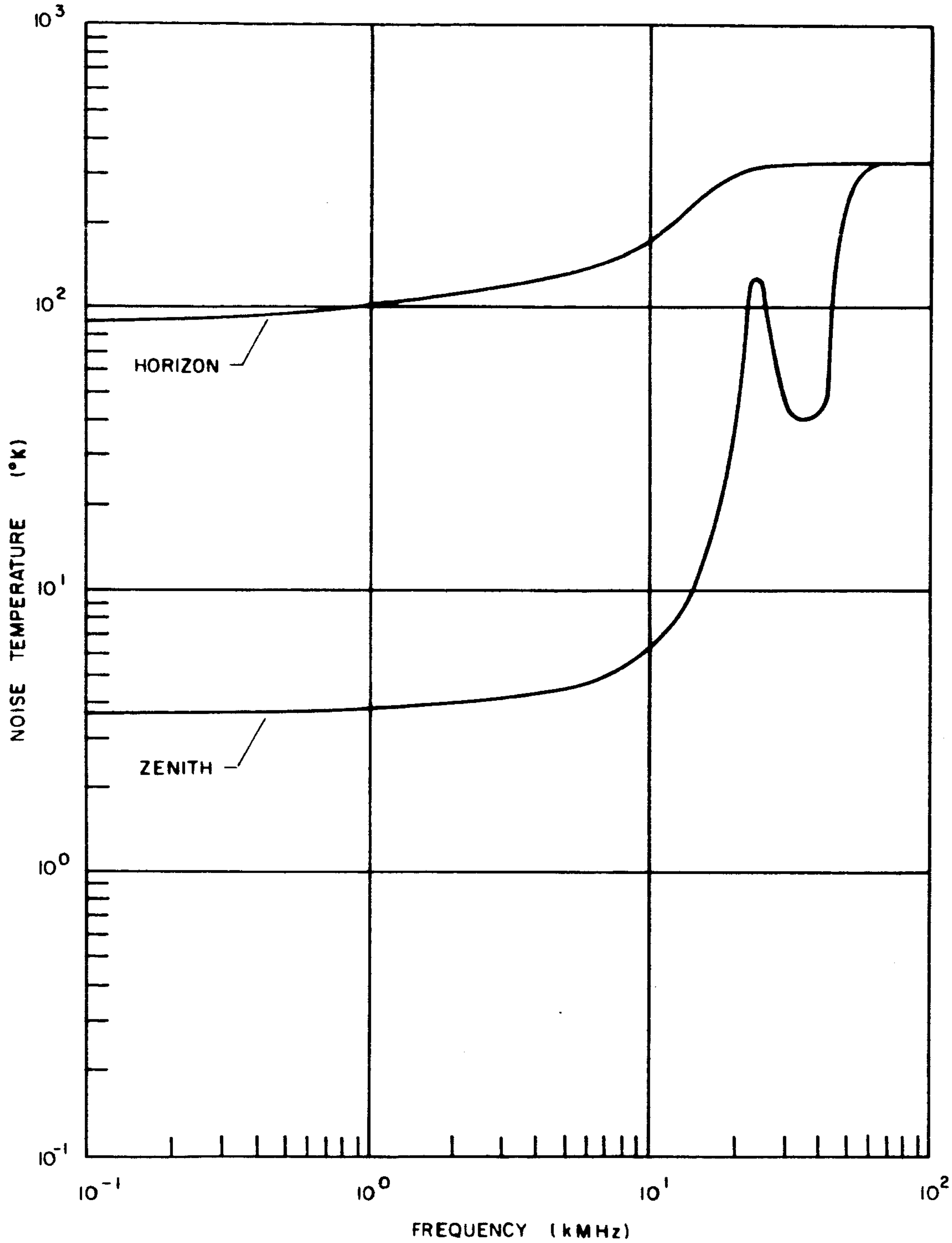

Figure 2-4. Atmospheric Noise

The result of combining the maximum cosmic noise (Figure 2-2), atmospheric noise (Figure 2-4), and noise due to sun burst and hydrogen emission is illustrated graphically in Figure 2-5. This, then, should be the worst average noise to expect when receiving signals from outer space.

2.5 AURORAL NOISE

During auroral conditions, the ionosphere can introduce a radiation loss of approximately 3 db at 30 Mc.[1] This loss decreases with the square of frequency and may be approximately 0.3 db at 100 Mc. It will decrease galactic noise but the aurora itself will add to the antenna noise temperature an amount equal to the product of the ionospheric electron temperature times its emissivity. The absorption-loss ratio minus one approximates the emissivity; it is 0.08 at 100 Mc and decreases with the square of frequency. The electron temperature in the ionosphere is less than a few hundred degrees.[1] Therefore, the aurora contributes less than 20 or 30°K to the antenna temperature at 100 Mc and much less at higher frequencies. Thus it can be considered negligible compared with galactic noise.

2.6 MAN-MADE NOISE

The man-made noise of greatest importance is that caused by electric switches, ignition mechanisms, and various types of electrical machinery. This type of noise is distance dependent and becomes relatively unimportant at distances greater than 20 to 30 miles from a typical city source. In an urban area this noise may be 35 db higher than cosmic noise at L-band frequencies. To realize this value of noise temperature, the antenna's main beam would have to be pointed directly at the source. An antenna located in a large city but pointing to the zenith would have a somewhat lower noise temperature level.

2.7 TERRESTRIAL NOISE

In general, noise generated by the earth will be picked up through the antenna sidelobes. The magnitude of this noise contribution will vary for

1. C. Little and H. Leinback, "Some Measurements of High Latitude Ionospheric Absorption Using Extraterrestrial Radio Waves," Proceedings of the IRE, January 1958.

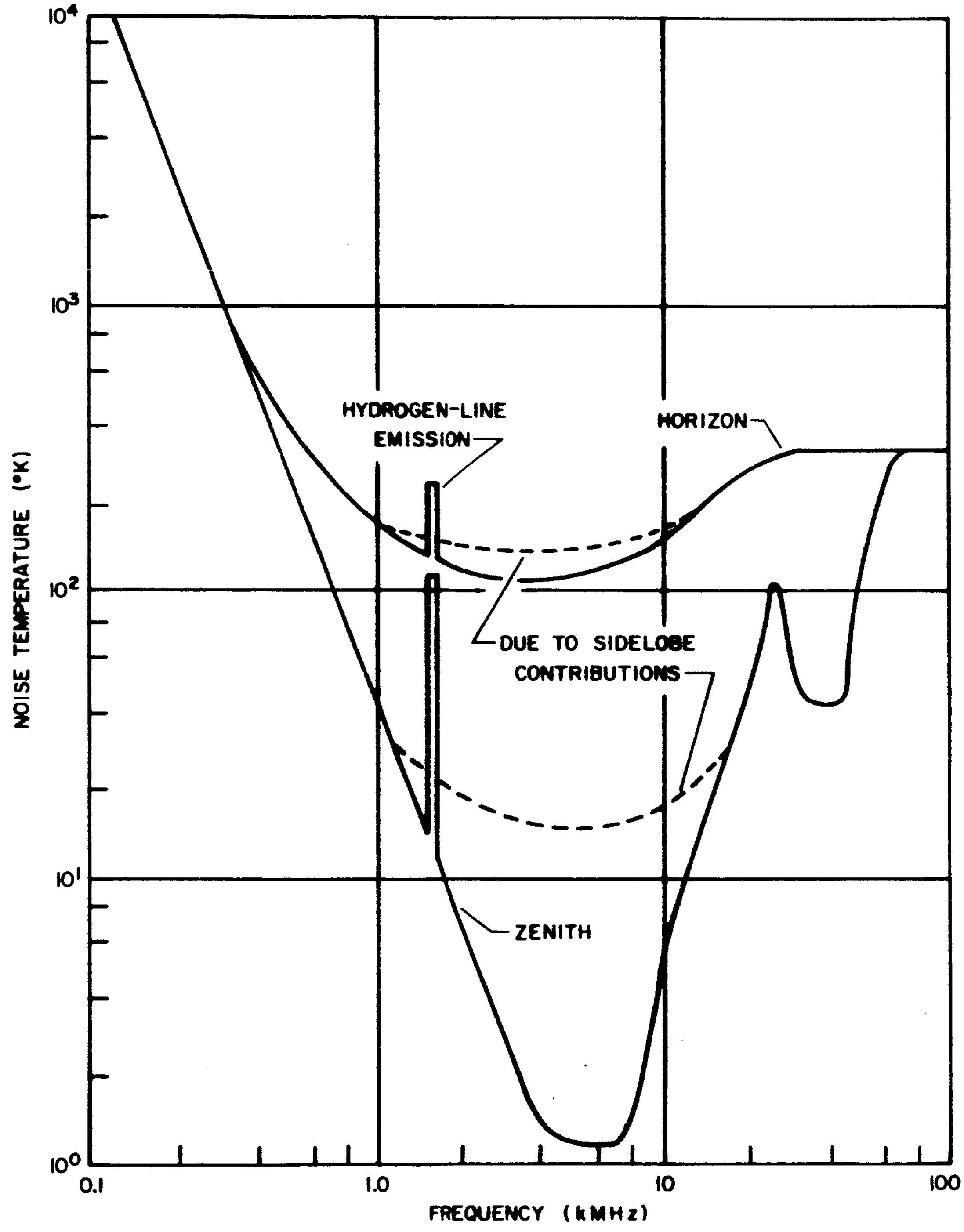

Figure 2-5. Antenna Noise

each antenna, depending on the side and backlobe levels and the elevation angle of the antenna. For a realizable antenna at an elevation angle of zero degree overlooking the sea, a total noise temperature of 147°K is realistic at 3 kMc.[1] This is based on the following assumptions: (1) a dish-type antenna with 85 percent of the power in the main beam and 15 percent in the side and backlobes, (2) an ambient temperature of the sea of 300°K and sea absorption of 0.81, and (3) an average galactic noise background of 10°K.

A similar case, computed for an L-band tropospheric scatter antenna, shows antenna noise temperature of about 135°K for zero-degree elevation angle and approximately 50°K for a 90-degree elevation.[2]

---

1. R. C. Hansen, "Low-Noise Antennas," Microwave Journal, Vol. 2, No. 6, June 1959.

2. J. L. Pawsey, and S. F. Smeral, The Sun, Chapter 7, University of Chicago Press, 1953.

SECTION 3

COMPARISON OF PERFORMANCE - MODULATION SYSTEMS

Speech-processing techniques which can reduce the redundant information in voice messages can be of significant utility in deep-space communications, since the system can reduce the noise bandwidth (noise power) significantly. The speech-processing system developed for NASA under the subject contract can produce intelligible speech at a bandwidth requirement of only 160 hertz. When we compare the new system with that of a conventional 3000-hertz speech system, we find that we have a bandwidth compression advantage of:

$$3000/160 = 18.75$$
$$= 12.7 \text{ db.}$$

In other words, under identical noise conditions, the output signal-to-noise ratio for the narrow-band system would be 12.7 db higher than for the conventional case. More specifically, the power requirements of the spaceborne transmitter can be decreased by 12.7 db to produce the same signal-to-noise conditions that would exist if a conventional speech-communication system were used. This power savings can be of significant value to any space mission, but would be of most use in deep-space missions where large power requirements are ordinarily necessary. Since power requirements are directly translatable to vehicle lift-off weight requirements, the use of speech-processing equipment might noticeably increase the efficiency of the mission.

It should be pointed out that the craft might transmit the information in its analog form, or the signal can be transmitted digitally at a rate of approximately 600 baud (using delta modulation). In many applications, the digital approach has distinct advantages; however, system performance is a critical factor of the modulation system used. The following subsections discuss the advantages and disadvantages of various modulation techniques.

3.1 ANALOG MODULATION SYSTEMS

Amplitude modulation systems, including conventional AM, DSSC, and SSB, have had limited application to space communications. The principal asset of these systems is the lack of an inherent threshold when demodulated by means of synchronous (linear) detectors. These systems, however, are vulnerable to interference and offer no means of SNR enhancement.

The angle modulation systems, FM and PM, provide a linear exchange of bandwidth for SNR as well as constant transmitter power and are amenable to a variety of effective disturbance-suppressing, signal-processing techniques. This exchange of bandwidth for SNR, however, is achieved only at the expense of a detection threshold at small CNR. Coherent demodulators such as locked-loop demodulators provide an effective means of threshold suppression and have received widespread space communications application.

Of the pulse modulation systems, PAM, PEM, and PPM, the latter is the most efficient. PPM is analogous to analog angle modulation in that it also exchanges bandwidth for SNR in a linear fashion and, as expected, has an inherent threshold. Pulse position modulation when modulated by a digital input is interesting in that, as described by Golay,[1] it promises a means of approaching the theoretical channel capacity. However, such a PPM system achieves high theoretical efficiency only if peak power is not limited by the transmitter.

3.2 DIGITAL MODULATION SYSTEMS

Digital modulation methods are of prime importance in space communications applications because they provide a practical approach to the bounds of communication theory. Digital methods make coding feasible, make efficient detectors such as correlation detectors practical devices, and permit more favorable tradeoffs of bandwidth for SNR. A disadvantage is in increased equipment complexity.

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1. M. J. E. Golay, "Note on the Theoretical Efficiency of Information Reception with PPM," Proceedings of the IRE, Vol. 37, No. 9, p. 1031, September 1949.

The basic digital modulation methods for binary coding are carrier keying, FSK, and PSK. The performance of these modulation methods in presence of thermal noise in terms of bit error probability, P_e, as a function of SNR^2 is shown in Figure 3-1. It is apparent from the figure that biphase PSK modulation, whether demodulated by a fully coherent or differentially coherent demodulator, yields the best performance.

It would be interesting to evaluate the narrow-band compression system when it was digitized at a 600-baud rate, and was transmitted using one of the modulation systems described in Figure 3-1. The performance for the speech system would first have to be evaluated in terms of the expected bit error rate. If we assume that the narrow-band system will work satisfactorily at an error rate of 10^{-2} or less, then the required signal-to-noise ratio would be about 6 db for a differentially coherent phase shift keyed system. Comparisons can also be made between a digital processed speech system and conventional types of digitized speech. For these comparisons the difference in performance is very closely related to the ratio of the bit rates for the two systems.

3.3 PULSE AMPLITUDE CODE MODULATION

Pulse amplitude code modulation (PACM)[1] offers a novel method of combining both analog and digital modulation. In PACM, PAM pulses and PCM bits are synchronously interlaced to form a single pulse train. PACM was developed specifically for multi-purpose telemetry applications with the intent of handling both moderate-accuracy analog data and high-accuracy digital data simultaneously.

3.4 ORTHOGONAL CODING

Efficient coding of the input information is of course essential to achieving optimum performance. Coding of information into sets of sequences characterized by low cross-correlation coefficients has the effect of reducing the error probabilities at the cost of expanding the bandwidth for a fixed rate of transmission. This coding technique is called orthogonal coding.

1. D. E. Gilcrest et al., "PACM-FM Telemetry Evaluation," NAECON Proc., Dayton, Ohio, p. 103, 1962.

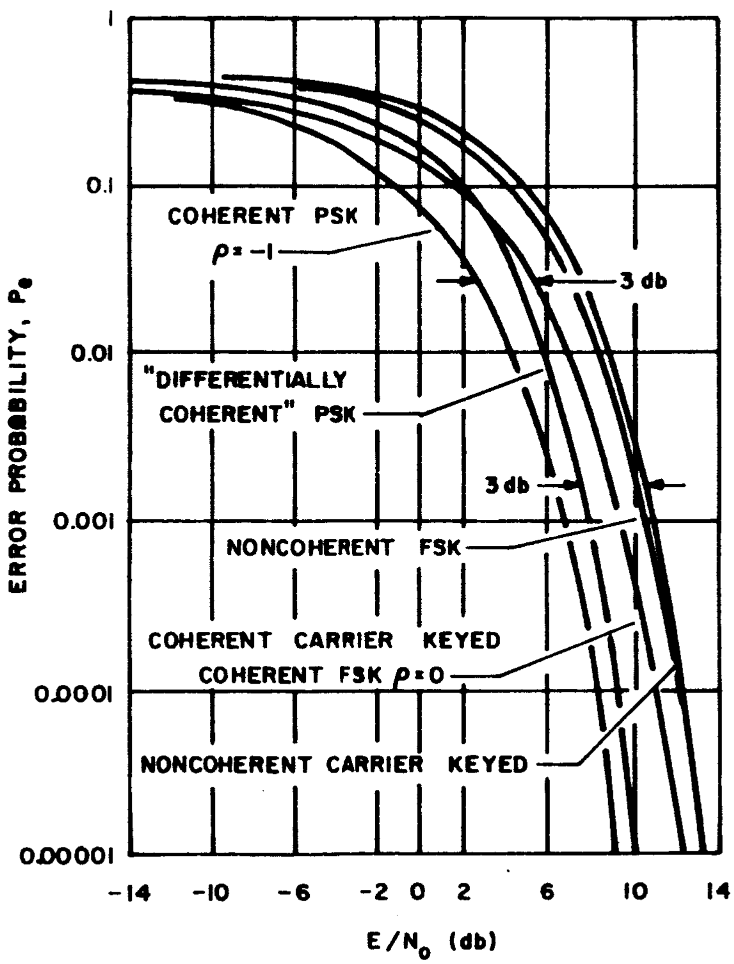

Figure 3-1. Probability of Error Versus
Signal Energy/Noise Power Density

Bi-orthogonal or Reed-Muller codes are generated by taking a set of orthogonal code words and adding to it the complements of each word. Bi-orthogonal codes require only one-half the bandwidth of the corresponding orthogonal set. The performance of the bi-orthogonal coding technique is slightly better than orthogonal coding for small n and equivalent for large n.

The use of coding techniques for advanced space communication systems should receive serious consideration because of the SNR improvement they afford.

3.5 MULTIPLE FREQUENCY-SHIFT KEYING

Multiple frequency-shift keying (MFSK) is the frequency domain counter-part of a pulse-modulation system in the time domain. MFSK is similar to frequency-shift keying with the exception that more than two frequencies are employed. The transmitter is keyed on any of the K frequencies, each determining a code element. Therefore, a code element represents $\log_2 K$ bits of information. (FSK is a special case of MFSK with K = 2.) The MFSK system, to achieve high theoretical efficiency, must transmit high-energy pulses which are narrow in the frequency domain. Therefore, high peak power is not required of the transmitter.

It has been shown at Philco[1] that MFSK achieves the maximum theoretical channel capacity, i.e., as K approaches infinity, the probability of a code element error approaches zero for

$$\frac{S_o T}{n_o} = \frac{\text{energy per bit}}{\text{Noise power density}} > \ell n^2 \qquad (2)$$

and approaches unity for

$$\frac{S_o T}{n_o} < \ell n^2. \qquad (3)$$

1. P. M. Hahn and C. Gumacos, Analysis of MFSK with Diversity, Philco RPA Report 621-9-4, September 1961.

Significant reductions in required signal energy for a given error probability are afforded by MFSK. The use of optimum modulation systems, such as MFSK, which approach the Shannon limit should receive careful consideration for long-range voice links.

3.6 PHASE AND FREQUENCY LOCK DEMODULATION

To minimize transmitter power requirements in space vehicles, angle modulation (FM and PM) is characteristically employed. Phase modulation in conjunction with phase-lock demodulation is generally preferred for narrow-band use,[1, 2, 3] while frequency modulation with either phase-lock or frequency-lock demodulation is the usual choice for wideband applications.[4, 5, 6] These are coherent demodulation techniques and therefore have similar noise-induced threshold properties. However, it has been shown[7] that the threshold in PM and FM feedback demodulators is caused not only by noise but also by modulation error. A comparison of phase and frequency lock FM demodulators for the case of FM deviated by a sine wave, is

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1. B. D. Martin, The Pioneer IV Lunar Probe: A Minimum Power FM/PM System Design, Jet Propulsion Lab. Technical Report No. 32-215, March 15, 1962.

2. A. J. Viterbi, "System Design Criteria for Space Television," Journal Brit. IRE, Vol. 19, No. 9, September 1959, pp. 561-570.

3. Hansen and Stephenson, "Communications at Megamile Ranges," Journal Brit. IRE, Vol. 22, No. 4, October 1961, pp. 329-345.

4. Gagliardi and Miller, "Minimum Power Wideband Communication System for Space Vehicles," 1961 National Telemetry Conference Proceedings.

5. L. H. Enloe, "The Synthesis of Frequency Feedback Demodulators," 1962 National Electronics Conference Proceedings, Vol. 18, 11. 477-497.

6. J. J. Spilker, Jr., "Threshold Comparison of Phase-Lock Frequency-Lock and Maximum-Likelihood Type of FM Discriminators," 1961 WESCON Proceedings 14/2.

7. L. H. Enloe, "Decreasing the Threshold in FM by Frequency Feedback," Proceedings of IRE, Vol. 50, No. 1, January 1962, pp. 18-30.

presented in Figure 3-2. In order to facilitate appraisal of these techniques, threshold performance curves are also given for the noncoherent ("ideal") frequency discriminator and the maximum-likelihood FM demodulators. (The maximum-likelihood demodulator is superior in performance because it is not constrained to real-time operation.) The curves for both phase lock and frequency lock pertain to systems having second-order transfer functions. As can be seen in Figure 3-2, phase lock is superior to frequency lock in threshold performance for small to moderate deviation ratios ($D < 25$), while frequency lock has the lower threshold when deviation ratios are high ($D > 25$).

Enloe has indicated that the apparent superiority of the FM feedback demodulator is due to its greater tolerance to modulation errors. Conventional phase-lock demodulators use as their VCO control signal the vector projection of the error phase ($\cos \theta$ or $\sin \theta$); therefore, operation becomes nonlinear for larger phase angles resulting in poor threshold performance. M. J. E. Golay's quadrature phase lock loop,[1] in which the filtered error phase itself controls the VCO, is inherently more linear than conventional phase lock and therefore should provide a lower threshold. Another attempt at a more linear control signal, "Tanlock,"[2] yields up to 4-db improvement in threshold over conventional phase lock.

When demodulators having more complex transfer functions are considered, phase- and frequency-lock demodulators are found to converge in threshold performance for high deviation ratios. It is to be expected that threshold improvement, via the route of using discriminator transfer functions of higher order, will encounter considerable difficulty because of analytic intractability and of stability requirements in the feedback loop.

---

1. Clark, Golay, Urban, Phase Lock Studies, Vol. II Philco Corporation, August 18, 1961.

2. L. M. Robinson, "Tanlock: A Phase-Lock Loop of Extended Tracking Capability," 1962 National Winter Convention on MIL Electronics Conference Proceedings, pp. 396-421.

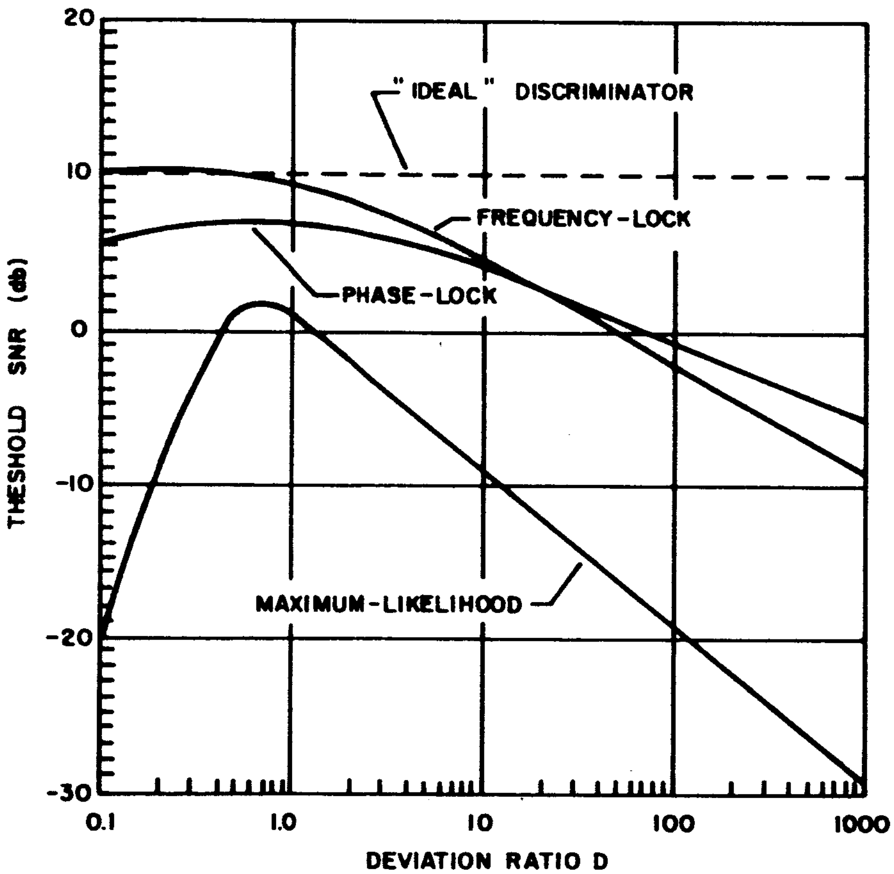

Figure 3-2. Comparison of Threshold Behavior of FM Demodulators

SECTION 4

CONCLUSIONS

From the previous discussions, it is clear the processor has significant advantages in performance over conventional systems. To illustrate how this advantage can be utilized, the application of speech processing to the lunar mission is examined. This example has been selected since the communication requirements are presently well defined. However, the conclusions drawn are generally applicable to any interplanetary mission.

The communication system in a mission of this sort must handle a number of functions including voice, telemetry, bio-medical data, ranging, and TV. Normally, several or all of these functions are multiplexed on a common carrier. For example, in the lunar down-link, ten distinct communication modes are described wherein different combinations of functions are combined. Table 4-1 lists these modes. A phase-modulated main carrier is employed. Voice is normally carried on a subcarrier except in the case of Mode 6, the backup voice mode.

The improvement in performance offered by the narrow-band system can be used to advantage in any one of several ways. When voice alone is transmitted, the margin provided by the system could be used to reduce the power, range, or the antenna gain by as much as 12.7 db, or to provide additional system margin, or some combination of the above.

When the voice is multiplexed with other functions, there are other tradeoffs possible. Table 4-2 shows the expected system margins for the lunar down link. Since each signal phase modulates a single main carrier, the margin for each signal will be proportional to the phase deviation which it imparts to the carrier. Therefore, if one signal deviates the carrier less, the deviation for another signal can be increased without changing the total deviation. In this way, the system margins can be distributed among the signals in any way desired. Therefore, the additional margin which the speech processor provides can also be distributed in any manner desired.

Table 4-1. LEM Down-Link MSFN S-Band Transmission Combination Summary

2282.5 Mc Carrier Combination	Information	Modulation Techniques	Subcarrier Frequency	Carrier Phase Deviation
1	Carrier			
	Voice	FM/PM	1.25 Mc	0.7 Radians
	51.2 kbps TM	PCM/PM/PM	1.024 Mc	1.3 Radians
2	Carrier			
	PRN	PM on Carrier		0.2 Radians*
	Voice	FM/PM	1.25 Mc	0.7 Radians
	51.2 kbps TM	PCM/PM/PM	1.024 Mc	1.3 Radians
3	Carrier			
	1.6 kbps TM	PCM/PM/PM	1.024 Mc	1.3 Radians
4	Carrier			
	BU Voice	PM on Carrier		0.8 Radians
	1.6 kbps TM	PCM/PM/PM	1.024 Mc	1.3 Radians
5	Carrier			
	Backup Voice	PM (24 db clipping)		0.8 Radians
6	Carrier			
	Key	AM/PM	512 kc	1.4 Radians
7	Carrier			
	Voice/Biomed	FM/PM	1.25 Mc	1.3 Radians
(Lunar Stay Mode)	1.6 kbps TM	PCM/PM/PM	1.024 Mc	0.7 Radians
8	Carrier			
	Voice/EMU/ Biomed	PM on Carrier (no clipping)		TBD
	51.2 kbps TM	PCM/PM/PM		
				Carrier Deviation Ratio
9	Voice/EMU/ Biomed	FM/FM	1.25 Mc	0.17
	TM	PCM/PM/FM	1.024 Mc	0.37
10	TV	FM at Baseband		2.0
	Voice/EMU/ Biomed	FM/FM/FM	1.25 Mc	0.17
	1.6 or 51.2	PCM/PM/FM	1.024 Mc	0.37

* Down PRN ranging phase deviation is to be set with up-voice and up ranging modulation (Table I Comb 3) and with a high signal-to-noise ratio in the turn around channel.

Table 4-2. Expected Circuit Margins
for Normal LEM Down-Link Combinations

System Configuration	Channels	Margin (db)
Steerable Antenna	Carrier	32.2
20 Watts	PRN Ranging	20.3
	Voice/Biomed	6.6
	Telemetry (51.2 kbps)	5.2
Erectable Antenna	Carrier	24.6
0.75 Watts	Voice/Biomed	3.2
	Telemetry (1.6 kbps)	5.8
Erectable Antenna	TV, Voice/Biomed, TM on	2.3
20 Watts	FM Channel	

* Assuming 85' ground station, T_{system} = 329°K, lunar distance.